SOME PRINCIPLES CONTROLLING THE DEPOSITION OF ORES.[1]

I WOULD hardly have ventured to talk on the subject of ore deposits to you if I had not approached the subject from a different point of view from the majority of men who have considered it. The point of view from which the subject of ore deposits has been most frequently considered has been that of a study of ore deposits themselves. A geologist or mining engineer has studied this or that ore deposit, or a number of ore deposits in different districts, and has then generalized concerning the ore deposits of other districts, and perhaps of the world. I also have considered the subject of ore deposits to some extent from that point of view, but if I had done this only, I would not have ventured to give a general address upon the subject.

Some years ago I took up the question of the alterations of rocks — the alterations of all rocks by all processes. In treating this subject it became necessary for me to consider somewhat fully underground water; the principles which control its flow; the manner in which it works; the results which it accomplishes. After I had reached certain conclusions upon that subject it seemed to me that the deposition of most ores was a special case falling under the general principles controlling the work of underground water. Therefore it is from the point of view of the circulation and work of underground water that I wish to consider the subject of ore deposits tonight. However, I cannot go into the subject fully, and will be obliged to ask those of you who are especially interested in it to refer to my more

[1] An address presented to the Western Society of Engineers at Chicago, June 13, 1900. The address is also printed in the journal of that society for December 1900.

This paper covers the same ground as a paper on the same subject, in a somewhat different form, which has already been published in the Transactions of the American Institute of Mining Engineers. Vol. XXX, 1900, pp. 1–151.

extended paper found in Vol. XXX of the *Transactions of the American Institute of Mining Engineers.*

There are three great classes of ore deposits; (1) those which are produced by igneous processes; (2) those which are produced by the direct processes of sedimentation; (3) those which are produced by the work of underground water. The last class is by far the largest, and it is the only one which I shall consider this evening.

My first, then, and my fundamental premise is, *That the most important class of ore deposits is the result of the work of underground water.* This premise I shall not attempt to prove; but because it is accepted by most geologists and by most mining engineers shall use it as a starting point.

My second fundamental premise is, *Ore deposits are derived from the outer crust of the earth, from that part of the crust of the earth which I have called the zone of fracture.*[1] There has been much discussion as to whether ore deposits are produced by descending waters, lateral-moving waters, or ascending waters. One of the most comprehensive papers which has been presented upon this subject was by Posepny.[1] In this paper Posepny holds that the original source of the metals of practically all the ore deposits of the class produced by underground water is the Barysphere (heavy-sphere), and therefore that the metals come from very far below the surface of the earth. The water in some mysterious way came from this heavy sphere, presumably very deep seated. The water rising from the Barysphere, where the rocks are supposed by some to contain more metalliferous material than near the surface, brought the metals of the ore deposits to their present positions. This view has been presented at great length by Posepny, ably argued, and he has had many disciples. Now it seems to me that the well-established principles of physics absolutely disprove this

[1] Principles of North American pre-Cambrian Geology, by C. R. VAN HISE: Sixteenth Ann. Rept. U. S. Geol. Surv., 1894–5, Pt. I, p. 589.

[2] The Genesis of the Ore Deposits, by F. POSEPNY: Trans. Am. Inst. Min. Engineers, Vol. XXIII, 1894, pp. 197–369.

hypothesis; and it further seems to me that observed geological phenomena also disprove it.

I have elsewhere divided the outer crust of the earth into zones, in descending order as follows: a zone of fracture, a zone of combined fracture and flowage, and a zone of flowage.[1]

Now, we will suppose that the crushing strength of the strongest rock is such that at a depth of twenty thousand meters below the surface the weight of the superincumbent rock (less the floating effect of underground water) is as great as the crushing strength of the rock. We will suppose that such a rock as the Berlin granite of Wisconsin, the strongest rock yet tested, having a crushing strength of 47,674 pounds per square inch,[1] extends from the surface to an indefinite depth. We will further suppose that in some way openings of some kind, say large cracks, are produced at the depth where the rock is under weight as great as its crushing strength. What would happen? You engineers know very well the rock would be crushed and the openings would close. Therefore at a depth of more than 20,000 meters below the surface of the earth, where the weight of the superincumbent rock is greater than the strongest rocks, if it be supposed that cracks of a considerable size could be formed, the pressure would crush the rocks and close the cracks. But the crushing strength of the great majority of the strong rocks does not exceed one half that of the Berlin granite. Moreover rocks at considerable depth are at higher temperatures than normal, and this probably weakens them. Consequently upon physical grounds we are prohibited from supposing that there are cracks and crevices of considerable size at more than a very moderate distance below the surface of the earth. But this conclusion does not rest upon physical principles alone. I have shown that there is another way besides crushing by which

[1] Principles of North American pre-Cambrian Geology, by C. R. VAN HISE: Sixteenth Ann. Rept. U. S. Geol. Surv., 1894–5, Pt. I, p. 589.

[2] Building and Ornamental Stones of Wisconsin, by E. R. BUCKLEY: Bull. Wis. Geol. and Nat. Hist. Surv., No. 4, 1898, p. 390.

rocks are readjusted to deforming stresses.[1] If the movement be slow and the temperature that of moderate depth the stress does not need to accumulate so that it shall be greater than the crushing strength of the rocks. Under such conditions, long before the crushing strength is reached, the contained water begins to act upon the material of the rocks and re-arranges it by continuous solution and deposition; so that it behaves as a plastic body. At all times the rock is a solid except for the infinitesimal amount held in solution; and yet it continually adjusts itself to the deforming stresses. A great many rocks which have been thus deformed under deep-seated conditions have a laminar structure which is analogous, not exactly similar, but analogous, to the leaves of a book. To make the analogy exact it would be necessary to suppose that the leaves are welded together, *i. e.*, held firmly by the molecular attractions between them. What has happened in the case of these laminar rocks? They have been transformed from a massive to a laminated form by recrystallization, but in many cases combined with mineral granulation and differential movements of the mineral particles. During the process of recrystallization, for each mineral particle, material is continually taken into solution on the sides where subjected to greatest stress and deposited on the edges where the stress is less, until the laminar structure is produced. The process of adjustment largely and in many instances mainly by continual solution and redeposition is rock flowage. Now rocks in which this process has taken place are found at the surface at many places. Moreover these rocks are frequently those of great strength. In many places it is certain that the amount of material which has been removed by erosion since the rocks were recrystallized is not more than 2000 or at most 3000 meters. Since, therefore, the process of rock flowage often takes place at much less depth than that at which rocks are crushed, it follows that large openings are not likely to exist at depths so great as above calculated for the closing of openings

[1] Metamorphism of Rocks and Rock Flowage, by C. R. VAN HISE: Bull. Geol. Soc. Am., Vol. IX, pp. 269–328, Pl. XIX.

by crushing. It is highly probable that few openings of appreciable magnitude exist at depths so great as 10,000 meters.

Therefore from the principles of physics and from observation we conclude that crevices and cracks of considerable magnitude do not exist below a very moderate depth. I would not say that minute cavities filled with liquid do not exist in the zone of rock flowage; I would not say that very small openings filled with gases may not exist in that zone; but there is every reason to believe that such cavities are exceedingly small. And it is well known that ore deposits in order to be of economic value must be of considerable magnitude. Such deposits were not formed in the minute and discontinuous openings filled with gas or liquid which very possibly exist at great depth.

But let us now consider this subject from another point of view. You as engineers know very well that the friction of a moving liquid increases very rapidly as the size of the passage through which it moves decreases. This is true even of super-capillary tubes. It is still more true of capillary openings, and the resistance goes up very rapidly as the capillary tubes decrease in size. When the openings become so small that the molecular attractions extend from wall to wall or the openings are subcapillary, the resistance is so great that the flowage is practically nil.[1] Now it is perfectly evident that a deposit of mineral material in an opening is not the work simply of the water that occupied it at any one time. Ordinarily, underground solutions of silica do not contain upon the average more than one part of silica per 100,000 parts of water, so that if an opening be filled with quartz, the most abundant of all the gangue minerals, we must suppose at least 100,000 times as much water went through the opening as there was quartz deposited. Therefore it is perfectly clear that the material for large ore deposits can only be gathered and the ores deposited in the zone where there is a vigorous circulation, and vigorous circulation is

[1] Metamorphism of Rocks and Rock Flowage, by C. R. VAN HISE: Bull. Geol. Soc. Am., Vol. IX, p. 272.

impossible in the deep-seated zone in which there are no continuous cracks and crevices of considerable size; hence the hypothesis of the derivation of the metals of the ores from the Barysphere is untenable. Valuable ore bodies have been deposited in openings and passages of considerable size and by a vigorous underground circulation. Since the magnitude of openings and vigorous circulation are correlative with, and exist only in the upper zone, that of fracture, the ores must have been derived from and deposited in this upper part of the crust of the earth.

If, then, we admit the fundamental premise, that the majority of ore deposits are the work of underground water, it seems to me that the conclusion cannot be escaped that the metals which are in the ore deposits are immediately derived from an upper zone, probably having a maximum depth of 10,000 meters, or seven or eight miles, in which the circulating waters are vigorous and effective.

However, I do not assert that now, or at any time in the past, metals for ores have not been derived ultimately from a deeper source through the agency of vulcanism, the medium of transfer being the igneous rocks. We do not know how deep down the igneous rocks which are intruded into the zone of fracture or flow out at the surface of the earth are transformed to magma, if they have not always existed as magma. We do not know very well the process by which the igneous rocks make their way up through the solid rocks of the zone of flowage. We do know, however, that they come from a very considerable depth, and take advantage of openings and cracks and crevices as soon as they reach the zone of fracture. For instance, in the Sierra Nevada, where there are various great sets of joints in the granite—vertical, inclined, and horizontal—the lava coming up from below has wedged itself into these joints, producing sets of parallel dikes. As these joints are utilized by the igneous rocks, so are openings of other kinds where igneous rocks intrude the zone of fracture. Igneous rocks in vast quantities as lava are poured out on the surface or as tuff fall upon it.

These igneous materials undoubtedly do in many cases bear metals out of which ores are made. But in few instances are they ores as igneous rocks. Igneous rocks so rich in iron as to serve as ores have been found on a very small scale. Vogt[1] holds that certain sulphide ores are produced directly by processes of differentiation of igneous rocks; but while I do not deny this, I also would not unqualifiedly assent to it. However this may be, there is fair agreement on the part of all that the great mass of the metals which come from the igneous rocks are derived from them through the agency of underground water, and that the ores which are now worked by man are preponderantly concentrates from the igneous rocks, or from the sedimentary rocks, or from the two combined. But if some ores have directly solidified as magma, they do not come within the scope of the discussion tonight; for I said at the outset that only ores produced by underground water would be considered. Such ores are probably derived for the most part from the upper 10,000 meters of the crust of the earth.

My third premise follows directly from the considerations already given: *If the waters below the zone of fracture do not circulate vigorously, and if vigorous circulation by underground water be necessary in order that ore deposits be produced, it follows that the waters which perform this work are of meteoric origin.* They are the waters which fall from the clouds upon the earth and sink into it. I do not deny that some small part of water concerned in the production of ores may be derived from below the zone of fracture; I do not deny that the igneous rocks rising from below bring with them small amounts of water; but these amounts are insignificant — are inappreciable in quantity as compared with the vast amount of water which is necessary to do the work of ore deposition. We know to a certainty that the great mass of underground circulating waters are of meteoric origin. For instance, if a well be drilled at Chicago through the limestones and shales near the surface

[1] J. H. L. Vogt: Zeitschr, für prakt. Geol., January and April 1893, October 1894, April, September, November, December 1895.

into the sandstone below you know that great quantities of water issue. The water falls upon the ground far to the northwest in central Wisconsin, where the sandstone reaches the surface. It follows this pervious formation below impervious strata, and when the impervious strata are punctured at Chicago rises to the surface through the opening. So it is with artesian wells everywhere. I repeat, *The waters which we know to be vigorously circulating are of meteoric origin, and these are the waters which have deposited the ores.*

We are now ready to pass to the fourth of my premises, viz., *The movement of underground water is mainly due to gravitative stress.* This is perhaps so plain to you as engineers that it will hardly need proving; but certainly many men who have written about ore deposits have given other explanations. Why does the water rise in the artesian wells in Chicago? Simply because the level of underground water at the northwest where the sandstone is fed is at a higher elevation. The difference in elevation is only a few hundred feet; and yet the difference in the weight of the columns, or the force of gravity, is sufficient to drive the water underground through the sandstone for a hundred or more miles to Chicago and make it rise considerably above the level of Lake Michigan. If the deformation had been such that the porous formation had somewhere been depressed nearly to the bottom of the zone of fracture, and the openings did not thereby become smaller, this in no way would have lessened the speed of circulation. It is therefore clear from our knowledge of artesian wells that a very moderate head is entirely adequate to account for an underground lateral circulation of great length and for a vertical circulation of great depth—entirely adequate to account for it. If this be true, why should we appeal to subterranean heat or to the unknown mysterious forces at the depths as a main cause for underground circulation?

I do not deny that in some cases water is squeezed out of the rocks by orogenic movements, nor do I deny that heat produces an effect in underground circulation. We may suppose,

for instance, that the water entering at one point issues at another point at the same elevation, after following a deep underground path. Suppose the water during the journey comes in contact with volcanic rocks, or suppose the water becomes warmer as the result of the normal increase in temperature with increased depth. We will suppose, for the sake of simplicity, that the temperature of the water is 0° C. where it enters the ground, and at a temperature of 100° C. where it issues. This is an extreme case, and beyond the facts; but it makes the illustration simple. During its journey the water expands as a result of its rise in temperature, and a unit volume of the issuing water weighs only about 96 per cent. as much as does a unit volume the entering water. The cooler or descending column contains a greater mass of water than the ascending column; it is, therefore, pulled stronger by the force of gravity; and consequently circulation takes place. The descending column falls and the ascending column rises because of the gravitative stress.

In the case of the Chicago artesian wells we have seen that the flowage is due to differential gravitative stress resulting from difference in elevation. In the case we have just considered, we have seen that the flowage is due to differential gravitative stress occasioned by difference in temperature. Therefore, underground water circulation caused by gravitative stress may be initiated by difference in head or difference in temperature, or by both combined. Ordinarily difference in head and difference in temperature work together. Commonly water enters the ground at a higher level than it issues; and I think it can be shown that water which is descending is, upon the average, at a lower temperature than water which is ascending, although I cannot stop to fully discuss this point. Therefore the descending column is heavier. Hence, unequal gravitative stress, caused by difference in head and by difference in temperature, is the adequate cause to which I appeal to account for the circulation of underground water which does multifarious kinds of geological work, a small part of which is the deposition of ores.

It is now necessary to consider in some detail the manner in which underground water moves. For a long time I have realized that if underground water had a difference in head that it might penetrate to a great depth and rise again to the surface;

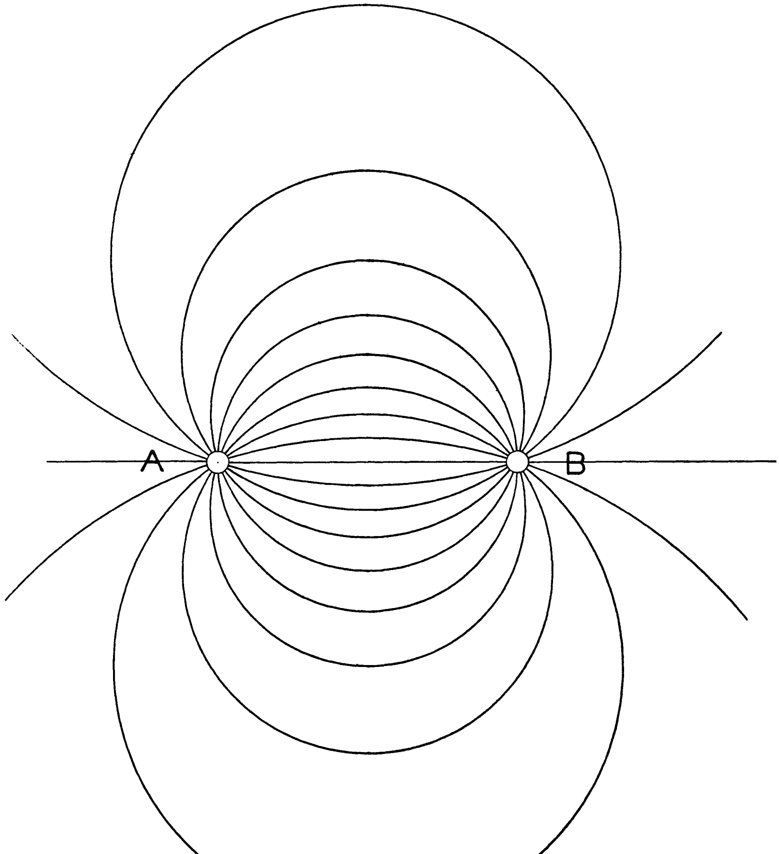

FIG. 1.

but I did not realize that it was not necessary to assume exceptional openings for such a circulation. I assumed that where such a circulation took place exceptionally favorable channels were available; but a recent paper by Professor Slichter[1]

[1] Theoretical Investigation of the Motion of Groundwaters, by C. S. SLICHTER, Nineteenth Ann. Rept. U. S. Geol. Surv., 1899, Pt. II, pp. 295–384.

upon the motion of groundwaters showed me that this was an entirely unnecessary assumption, and gave me the additional data needed upon this point. This chart (Fig. 1) is a horizontal diagram. A represents one well and B another well, separated by a homogenous porous medium. Into the well B, I pour water. In the well A there is no water at the outset; and the water flows from the well B to the well A through the medium. What is the path of the water? Its flowage is represented by the curved lines. Some of the water goes in a nearly direct course. Another part takes a somewhat curved course. Still other parts of the water follows a very indirect course, represented by the longer curved lines. All of the available cross section is utilized. If for instance this room were filled with water, and water were running in at one place in the front end of the room and were escaping at one place in the rear end of the room with equal speed, would the water simply follow the direct line between the two? You know perfectly well it would not. The entire available cross section of the room would be utilized, although the more direct course would be utilized to a greater extent than the more indirect course. This is intended to be illustrated on the chart (Fig. 1) by the lines representing the nearly direct courses being close together, and the lines representing the indirect courses being farther apart.

This chart (Fig. 1) then represents the horizontal circulation. If we pass to the vertical circulation the flowage is represented by this chart (Fig. 2). The water is being poured into the well B and passes to the well A. The water follows the course of the curved lines, so that with a difference in head equal to the difference in the level of the water in the two wells, a considerable part of the water being poured into B and passing through the homogenous porous medium to A penetrates a considerable depth, from which it rises and enters the well A. Now what will be the limit in nature of the downward search of underground water? We have already given it. Manifestly the lowest limit of effective circulation at any place is the bottom of the zone of fracture at that place. The zone of flowage

below is practically impervious. However, an impervious limiting stratum may exist at depths far less than the bottom of the zone of fracture. An impervious limiting stratum, perhaps a shale, may be found at a depth of 100 meters or less, or at any

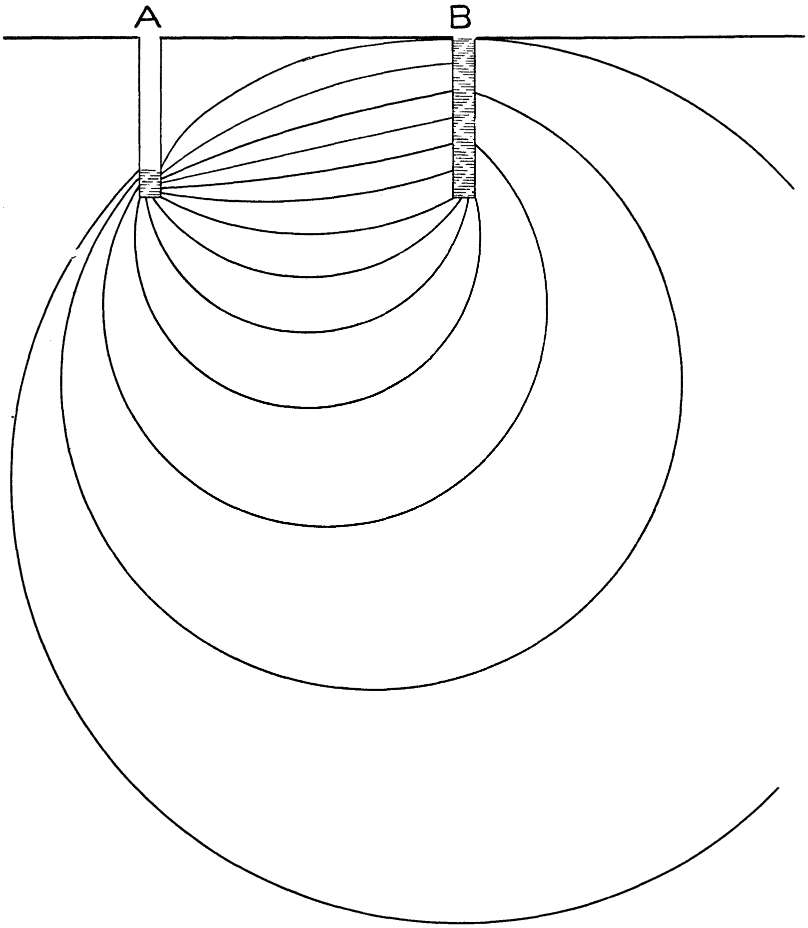

FIG. 2.

depth intermediate between this and the bottom of the zone of fracture for the strongest rocks. Where there are one or more pervious strata which are inclined and above, below, and between which are impervious formations, there may be two or more

nearly independent circulations. To illustrate, at Chicago the St. Peter's sandstone, the Potsdam sandstone, and even different parts of the Potsdam sandstone have more or less independent circulations. If a limiting stratum be supposed to be half-way down on the chart (Fig. 2) the lines of flow above this stratum would not be as they are now, but would be flatter and would be limited by the impervious rock.

Under natural conditions wherever there is an impervious rock there is a limit of some particular circulation in that direction. A limiting stratum may therefore be very near the surface, at the bottom of the zone of fracture, or at any intermediate depth; and theoretically a moderate head is sufficient to do the work of driving the water to any of these depths. Indeed, there is no escape from the conclusion that at least some circulation does occur in the deeper parts of the zone of fracture with a very moderate head. Of course in proportion as the head is great the circulation at depth is likely to be vigorous. But it may be objected that a deep circulation, while theoretically possible, must be exceedingly small in quantity, and consequently of comparatively little account in the deposition of ores. But the consideration of the underground circulation in reference to the Chicago artesian wells, shows that this objection has little weight. (See p. 737.) Moreover, the deeply circulating water, if less in quantity than that near the surface, takes a longer journey and is longer in contact with the rocks through which it is searching for the metals. Not only so, but it is at a higher temperature than the water at higher levels; and this also is favorable to taking mineral material in solution. And, finally, because it has a higher temperature it has less viscosity. While the variable viscosity of water is not so very important in reference to circulation in super-capillary tubes, in capillary tubes, which constitute a very large fraction of underground openings, and especially those at considerable depth, the viscosity is important —the flowage increasing directly as the viscosity decreases. The viscosity of water at 90° C. is only one fifth as much as it is at 0° C.; and therefore with a given head of water in capillary

tubes, if the temperature be considerably increased—and but a moderate depth is required to give considerable increase—the water moves several times as fast as it would at the surface under conditions similar in all respects save temperature. Therefore, because of these three factors, long journey, high temperature, and low viscosity, we cannot exclude the deep circulation from consideration. This circulation is indeed believed to be very important in the deposition of ores.

We are now prepared to consider the actual journey of underground water. Where water falls upon porous ground it finds innumerable openings through which it enters and begins its underground journey. This circulating water, as far as practicable, under the law of the minimum expenditure of energy, follows the paths of easiest resistance. But these are the larger openings, because resistance due to friction along the walls and within the current is very much less per unit circulation in large than in small openings. While therefore water enters the ground at innumerable small openings, as it goes down it more and more seeks the larger openings. Once found, it holds to them. The farther it continues its journey, the greater the proportion of the water which follows the larger openings. But if this be true, the water in its descending course is more likely to be widely dispersed and in the smaller openings; and in its upward course more likely to be concentrated and in the larger openings.

We can now follow the course of underground water in detail, but in doing this it is necessary to consider the elements of the problem separately. It is only by passing from a simple case to the very complex one of nature that we can understand the latter. Here is a chart (Fig. 3) which shows the surface of a slope, the level of groundwater, and the flowage of water in the simplest imaginable case. Below the level of groundwater all the openings in the rocks, great and small, are filled with water. The rocks are saturated. In the case represented I have supposed that all of the water enters at a single point, A; and that all of it issues at a single point, B. The curved lines represent the

flowage of the water through a homogeneous porous medium. In the next chart (Fig. 4) I have supposed water to enter at three points and issue at one; and I have supposed the flowage from each point of entrance to occur just as if no water were

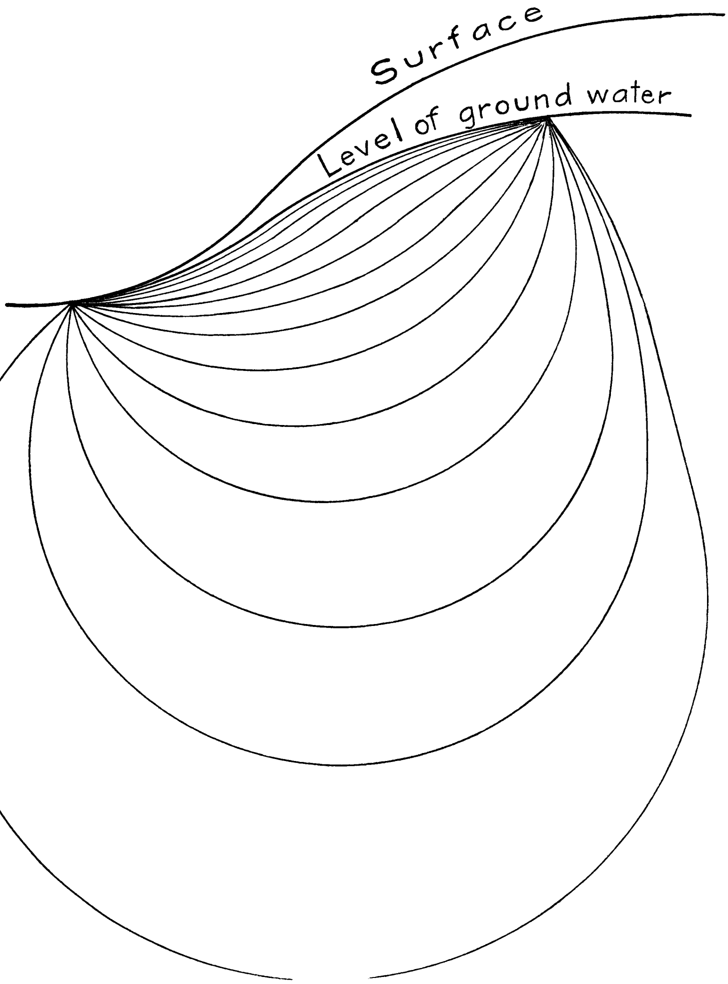

FIG. 3.

entering anywhere else, and therefore the systems of flowage to be superimposed. Of course this is not a real case. Underground water does not diverge from a single point and converge at another point in independence of the water entering

at other points. The water entering at innumerable points in vertical section and in horizontal section mutually interfere, and make the course for any given particle of water rather simple.

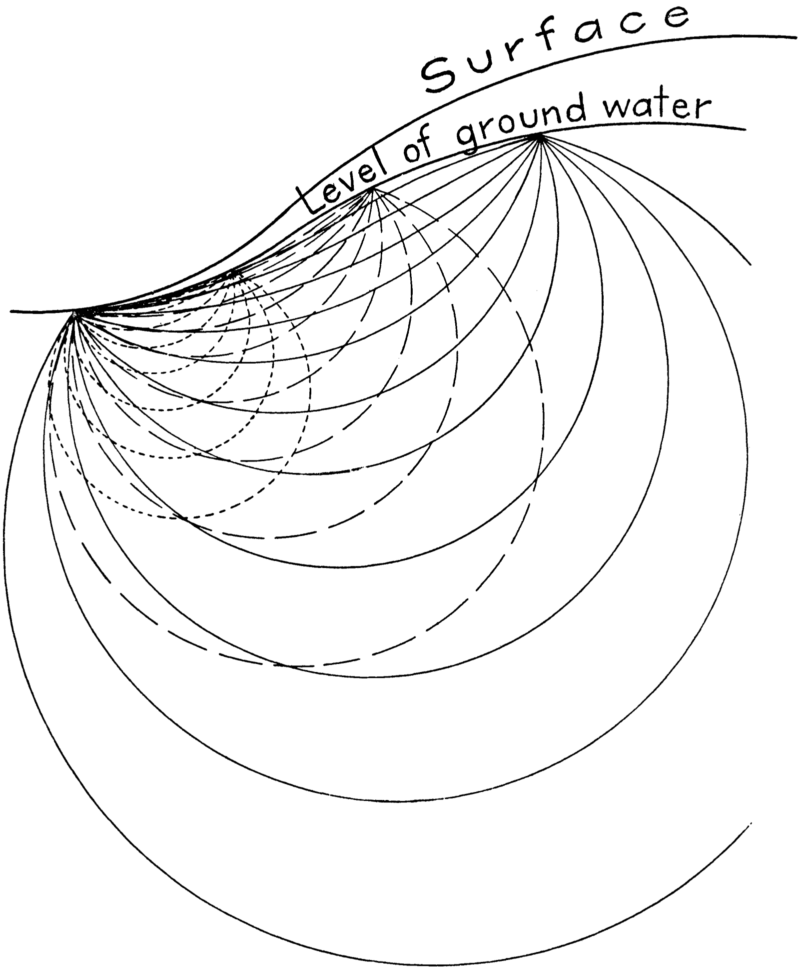

FIG. 4.

This I have tried to represent by another chart (Fig. 5). In this chart I have supposed particles of water to enter at equal horizontal intervals, and issue at a single point. You note that the water near the crest begins its journey by almost vertical

descent. In proportion as the entering water is near the valley the horizontal component becomes more important. The water near the valley follows a comparatively shallow course; but this water uses all the available space near the surface, and conse-

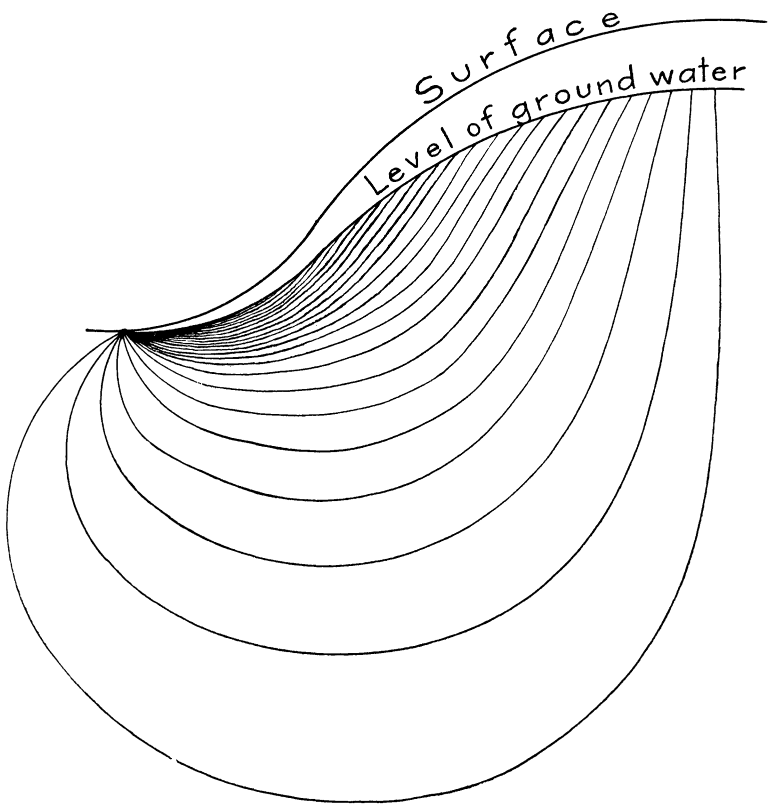

FIG. 5.

quently the water entering at the higher ground necessarily follows a long, circuitous, and deep course. The chart (Fig. 5) therefore represents the flowage with many points of entrance and a single point of exit, where there is interference of the circulating waters.

Thus far it has been supposed that the ground is uniformly porous, like an evenly grained sandstone without joint or fracture

of any kind, in which the water can go in all directions with equal ease. But absolute uniformity does not exist in nature. The openings in rocks are never of uniform size; they are never equally distributed. Suppose half way down the slope

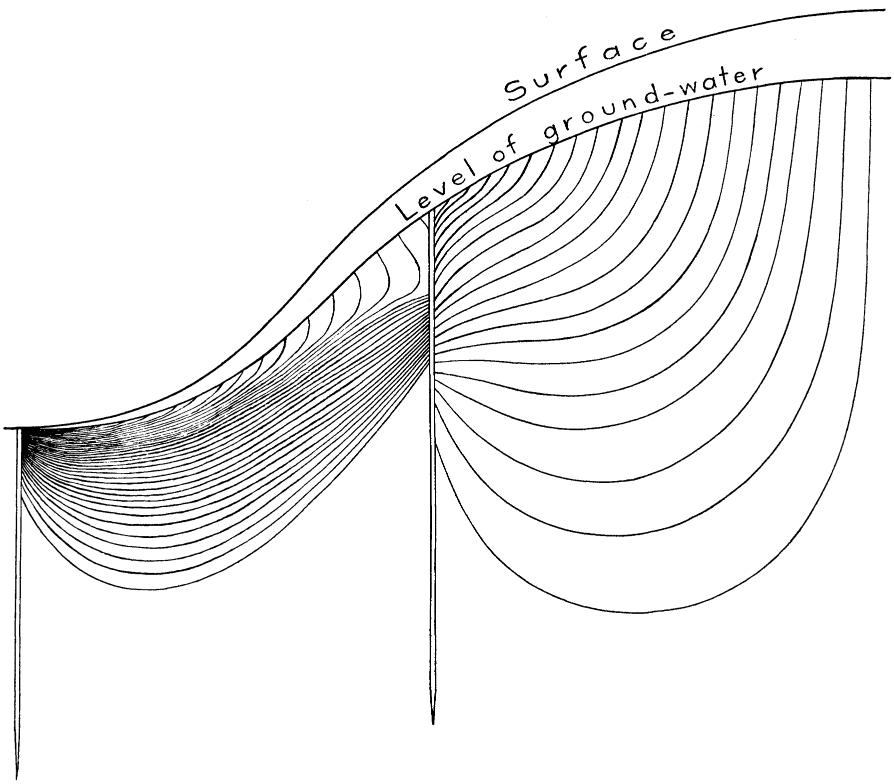

FIG. 6.

there is a vertical opening of unusual size transverse to the plane of the chart (Fig. 6), and another similar opening below the valley. If you please, we will call them fissures. These fissures, because large openings, will be fully utilized by the underground water. We readily see that groundwater will enter the higher fissure at many points and from various directions. Ordinarily it will enter the upper part while it is still descending; it will

enter the central part laterally; it will have begun its ascent before it enters the lower part. Therefore a fissure upon the middle of a slope will be very likely to receive water from above, from the side, and from below. But at a certain area of a fissure well up on the slope the water continuously received at the upper side of the fissure will escape laterally at the lower side. This water and that entering the ground below the upper fissure will make its way to the fissure below the valley. But here the level of groundwater is at the surface. Consequently all the water entering this fissure will ascend quite to the surface, and issue as a spring. If there be a fissure at the crest we can see that the descending water will go a long way down; but the waters will nowhere be ascending. If there be a fissure on the slope, both descending and ascending waters will ordinarily be active; although it is of course recognized that in fissures thus located the conditions may be such that the waters will ascend or descend only. If there be a fissure below a valley where the level of groundwater is at the surface the water will all be ascending; and there will be no descending water. At such places we have springs. Springs do not issue from the tops of mountains, but from slopes and valleys, most frequently the latter. Illustrating this are the Yellowstone Park springs of the Firehole River. The waters which feed the springs fall upon the crests and slopes of the mountains adjacent; on their way to the valley go deep below the surface, and at the Firehole ascend as hot springs and geysers. The water is driven by gravity due to a considerable head and the lower temperature of the descending column.

You are all doubtless aware that three theories are maintained as to the source of the waters which deposit ores. Some hold that the waters doing the work are descending; others that they enter laterally; others that they are ascending. The first is known as the descension, the second as the lateral secretion, and the third as the ascension theory. If my argument be correct as to a limit to the zone of fracture, fissures, as well as all other openings, must gradually become smaller and smaller,

and finally die out altogether. Water in a fissure may descend or may ascend for a considerable distance; but it is perfectly clear that, so far as fissures are concerned, except for the small amount entering the surface openings, the water must enter laterally. Consequently, if we apply the lateral-secretion theory broadly enough, we may say that all the waters which feed the fissures are lateral-secreting waters. But if we are descensionists, and consider only the upper part of a fissure on the slope—and that is what many very naturally have done because this is the part of the fissure most easily observed—we may say that the waters which are doing the work are descending waters. Or, if we are in such a district as that of the Comstock lode, in which are found great volumes of ascending water, we may say that the waters which are depositing the ores are ascending. All may be true. But in the past Sandberger held that lateral-secreting waters in the narrowest sense did all the work, and he refused to believe that ascending and descending waters were of importance; and Posepny held that ascending waters did nearly all the work, and gave small consideration to lateral-secreting and descending waters; whereas you see with perfect clearness that each theory is incomplete. Both are needed; they supplement each other.

Passing now to the work of underground water, we find there are very great differences in the nature of the work which takes place above the level of groundwater and below the level of groundwater. The first is called the belt of weathering; the second the belt of cementation[1] (see Fig. 7). Also there are great differences in the work which takes place in the zone of fracture, which includes both the belts of weathering and cementation, and that in the deep-lying zone, that of rock flowage. All of these differences have a very close bearing upon some phase of ore deposition. But the subject is too complex for me to take up fully, and I shall simply give the major differences in the reactions without stopping to demonstrate their

[1] Metamorphism of Rocks and Rock Flowage, by C. R. VAN HISE: Bull. Geol. Soc. Am., Vol. IX, p. 278.

correctness.[1] Above the level of groundwater, in the belt of weathering, the chemical reactions of oxidation, carbonation, hydration, and solution are the rule. The mechanical results are disintegration, softening, and decomposition of the rocks. Below the level of groundwater, in the belt of cementation, the chemical reactions of oxidation and carbonation are less active; but hydration occurs very extensively. Instead of solution, deposition is continually taking place. The mechanical result is that the rocks, instead of being disintegrated, softened, and decomposed, are hardened, the openings being cemented. Where comes the material for cementation? Why, from this belt of weathering

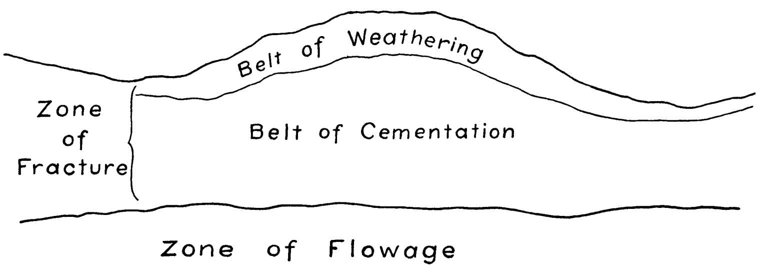

FIG. 7.

above, where solution is taking place. If the waters in the belt of weathering are continuously taking materials into solution, and are continuously depositing material below, as denudation goes on these belts steadily migrate downward. The present belt of weathering not long ago geologically was in the belt of cementation. While, therefore, the belt of weathering at any given time in the past, as now, was relatively thin, it may have moved downward for thousands of feet. In many mining districts it is estimated that from 1000 to 3000 or more meters of rock have been removed from above the present surface. All of this thickness has been in the belt of weathering; although at any one time the belt of weathering may have been but a score or few score meters in thickness. Therefore, from the belt of weathering a great and adequate amount of material may

[1] For a fuller discussion see Metamorphism, cit., pp. 277–286.

have been derived to fill the cracks and crevices of the entire belt of cementation below, although this belt may be thousands of meters thick. This process of filling cracks and crevices by deposition is the general law for the great belt of cementation below the level of groundwater, just as certainly as solution is the general law for the belt of weathering above the level of groundwater. These are the dominant processes. However, I by no means assert that deposition does not occur in the belt of weathering, and that solution does not occur in the belt of cementation. Indeed, the solution of material in various places, in both the belts of weathering and cementation, and the deposition of this same material or a part of it in the same belts at other places are very important processes.

We therefore conclude that the solution of material in the belt of weathering and the deposition of material in the belt of cementation, and the solution and deposition of material within the same belts, fills the openings in the rocks below the level of groundwater. These processes are gradually changing the soft sandstones, such as exist below the surface limestone of Chicago, into quartzite. By the same processes fractures—small and great, from minute joints to great fissures—are filled by deposition of material from underground waters. The formation of ore deposits is largely an incident of this process. The volume of material transported from the belt of weathering and deposited below in the openings of the belt of cementation, and transferred from place to place within these belts, is many million times greater than the ore deposits. The development of ores is merely an exceptional case of a widespread and most important geological process, the deposition of ores involving only a consideration of the particular materials which are of value to man. This evening I propose very briefly to discuss the source of such materials: how they are carried; why and where they are deposited. The particular case is under the general laws which control the general process of solution and deposition.

There are a great many chemical laws which affect the process of ore deposition, and a few of them I am obliged to

mention. The first law is: All the elements and compounds of nature are soluble to some extent in water. If water be placed in contact with an hundred substances, it will hold some part of every one of those substances in solution. It follows that if, in the journey of underground water, it finds here and there gold or silver or lead or zinc or iron, in quantity small or great, those materials to some extent will be taken into solution. The second law is the fundamental principle of chemical dynamics, viz.; Chemical action is proportional to the active mass. To illustrate, other things being equal, the greater the quantity of a compound present, the greater the quantity which will be taken into solution and deposited from solution.

The materials will be likely to be taken into solution in large measure during the descending course of the water; and deposited from solution in large measure during the ascending course of the water. For this there are a number of reasons. First, solution is likely to occur during descension because the conditions are those of increasing temperature and pressure. It is well known that increase of temperature greatly increases the solvent power of water. In many cases a slight rise in temperature is sufficient to increase this activity in an amazing degree; in fact out of all proportion to the increase of temperature. Deposition is likely to occur during ascension because the conditions are those of decreasing temperature and pressure.[1] Second, some substances are held in solution better than others. Certain substances, such as quartz, may be deposited during the downward course of the water, and a more soluble substance, such as gold, silver, or some other substance, be dissolved at the same time. Third, the larger openings, such as fissures, are the trunk channels of water circulation. In them the waters from different sources mingle; and this to my mind is the most important single factor—probably the dominant factor,

[1] The relations of temperature and pressure to solution and precipitation are much more complicated than implied in the above general statement. For a more nearly exact expression of the facts see Some Principles Controlling the Deposition of Ores, by C. R. VAN HISE: Separate from Trans. Am. Inst. Min. Engineers, Vol. XXX, 1900, pp. 38–43.

in the precipitation of ores. If the contents of half a dozen test tubes filled with solutions chosen at random be dumped together, a precipitate is almost sure to form. And just so sure as underground waters come from this source and that source and mingle in the trunk channels of underground circulation, just so surely are precipitates formed. Fourth, in the formation of an ore deposit the wall rock may contribute a solution which precipitates a metal, or it may contribute a metal which is precipitated by a solution. Consequently an ore deposit may be confined to a particular horizon where there is a certain rock. For instance, lead and zinc are very generally associated with limestone, and the sandstones or other rocks above or below are very likely to be deficient or nearly devoid of these metals. To a less extent other ores show a decided preference for limestone as compared with other rocks. The explanation may be that the limestone itself furnishes the material; and this is believed to be the fact in various cases. The explanation may be that the limestone furnishes a precipitating agent to solutions derived from other rocks. It may be that the limestone because of its ready solubility furnishes large openings in which big deposits may be formed. Finally the explanation may lie in the combination of two or more of these factors. I have no doubt if we consider the whole world each of these factors is important, and that in some cases all of them coöperate. As a result of the combination of the various factors above considered a porous rock or an opening once in a million or ten million times receives enough of the metallic materials in solution so that a fraction of an ounce of gold per ton, or a few ounces of silver per ton, or a few per cent. of copper or some other metal, or a large per cent. of iron, will be precipitated; and we call the material an ore deposit. An ore deposit it is from an economic point of view. From a geological point of view it is usually to a far greater extent quartz and calcite and other gangue minerals.

I wish now to go a little further and consider the fissure on the slope shown in this chart (Fig. 6), both in the past and the

present. At some distant time in the past suppose the surface and level of groundwater, instead of being as shown, were at much higher levels, having since been greatly lowered by the processes of denudation. Where would the upper part of the fissure shown, the water of which is descending, be with reference to the circulation at that time? It would be where the lower part of the fissure now is, would it not? It would be where the waters are ascending, as shown in the lower part of the fissure. Therefore for the part of the fissure where the water is now descending it may be that the first contribution of ore was made by ascending waters, although descending waters are now the only important factor. But as denudation went on the condition would gradually change. The part of the fissure under consideration would pass through a stage in which the waters would mainly come in laterally. As denudation went still farther the waters might all be descending, and in the extension of the fissure below the waters might come in laterally, and still deeper might be ascending. We must now still further amplify our theory, must we not? To explain the entire ore deposit we have to consider all parts of the ore deposit throughout its entire history. At present ore deposition by descension, by lateral secretion, by ascension, is somewhere occurring in the fissure; but not only is this the case, but all have worked in turn in the upper part of the deposit. Therefore this further complicates the theory of ore deposition.

Now I wish to give some facts as to the actual occurrences of ore deposits before I go to the next step in theory. At Butte, Mont., are famous copper deposits. In the copper lodes of this district, in the very upper part of the deposits, above the level of groundwater, there were oxidized ores which carried high values in silver and gold, but very low values in copper. At and a short distance below the level of groundwater there were very high values in copper as sulphides. "There follows below a region of varying height, of valuable rock, which again slowly deteriorates in depth; this deterioration, however, being so retarded finally as to be scarcely

appreciable."[1] This deep ore is mainly copper-bearing pyrites. Douglass tells us that in depth every copper deposit of the entire Appalachian region of the United States shows only cupriferous pyrrhotite. An excellent illustration is Ducktown, Tenn., where at the level of groundwater was a very rich deposit of chalcocite but a few feet thickness which rapidly changed into very low grade cupriferous pyrrhotite.[2] In Australia down to the level of groundwater are high values in native gold; below the level of groundwater are auriferous pyrites bearing relatively small values of the precious metals.[3] Some of the superintendents say where ounces of gold are found above the level of groundwater only pennyweights are found below.[4] In the Sierra Nevada of the United States, according to Lindgren,[5] above the level of groundwater the gold values ran from $80 up to $300 per ton; but below the level of groundwater where there are sulphurets the values average from $20 to $30 per ton. Notwithstanding the fact that occurrences such as those mentioned are typical of the ore deposits of many districts of the world it has been believed by very many practical mining men that ore deposits become richer upon the average with increase of depth; but it must be admitted that the facts do not justify this sanguine expectation. In fact nine mines out of ten, taking the world as a whole, are poorer the second 300 meters than they are the first 300 meters, and are poorer the third 300 meters than they are the second 300 meters. In fact, many

[1] The Ore Deposits of Butte City, by R. C. BROWN: Trans. Am. Inst. Min. Eng., Vol. XXIV, 1895, p. 556.

[2] The Persistence of Lodes in Depth, by W. P. BLAKE: Eng. Min. Jour., Vol. LV, 1893, p. 3.

The Ducktown Ore Deposits and Treatment of the Ducktown Copper Ore, by C. HENRICH: Trans. Am. Inst. Min. Eng., Vol. XXV, 1896, pp. 206–209.

[3] The Alterations of the Western Australian Ore Deposits, by H. C. HOOVER: Trans. Am. Inst. Min. Eng., Vol. XXVIII, 1899, pp. 762–764.

[4] The Genesis of Certain Auriferous Lodes, by J. R. DON: Trans. Am. Inst. Min. Eng., Vol. XXVII, 1898, p. 596.

[5] The Gold-quartz Veins of Nevada City and Grass Valley, California, by WALDEMAR LINDGREN: Seventeenth Ann. Rep. U. S. Geol. Surv., 1895–6, Pt. II, p. 128, 1896.

ore deposits have been exhausted or have become so lean as not to warrant working before the 300 meter level is reached; a large proportion before the 600 meter level is reached; while comparatively few ore deposits have been found to be so rich as to warrant working at depths greater than 1000 meters.

There are however some ore deposits which are not known to decrease in richness with depth so far as yet exploited. There are a considerable number of deposits in which after a first rapid decrease in richness maintain their tenor pretty well to the depth of 300, 500 or even 1000 meters, and some few deposits maintain their richness at even greater depths. But we cannot reasonably hope that a deposit will get richer with depth provided we use a 300-meter unit for measurement. The most sanguine view which is ever justified for any deposit is that, using a 300-meter unit, that the second shall be as good as the first, and the third as good as the second. While the above is true there are very great irregularities in the richness of ore deposits, both favorable and unfavorable, due to multifarious causes, which I cannot possibly discuss tonight, but which I considered somewhat fully in the Institute paper.[1] These irregularities are especially marked in the upper 300 meters of a deposit; so that in many cases if the unit of measurement were 10 meters or 30 meters, or in a few cases 100 meters even, it might be said that deposits are becoming richer with depth; although the reverse also occurs in many cases. The truth is that in the uppermost part of an ore deposit the variations in richness with depth are extreme, and no definite rules can be laid down in reference to them.

Now what is the explanation of these irregularities and of the very general diminution of richness with depth? What is the explanation in some cases of the relatively even values at variable depth? The last question will be first considered.

In those instances in which the tenor is maintained or practically maintained from the surface to a great depth the ore

[1] Some Principles Controlling the Deposition of Ores, by C. R. VAN HISE: Trans. Am. Inst. Min. Eng., Vol. XXX, 1900, pp. 102–112.

is believed to be the result of a single concentration by ascending waters. Such ore deposits may continue without any appreciable diminution in richness to the lowest limits to which man may expect to penetrate the earth; but these are exceptional cases. Even ore deposits which are the result of a single concentration by ascending water may diminish in richness at considerable depth. It has been seen that in the fissure at the bottom of the valley on this chart (Fig. 6) that the water ascends to the surface. It is evident that the upper part of the fissure receives the greatest supply of water, and this water to a large extent does not penetrate any great depth; while the lower part of the fissure receives less water, but this water penetrates to a considerable depth. It may happen that the water relatively near the surface traverses the rocks containing the main supply of metals and therefore brings the chief contributions of valuable material, or such waters may carry the precipitating agent. In such instances the ore deposits produced by ascending water alone, would diminish in richness with depth; but such decrease would not be likely to be very rapid. Upon the other hand, if the above conditions be reversed, a deposit may increase in richness for a considerable depth; but as a matter of fact this appears to be a very infrequent case.

As illustrations of the ore deposits of the class produced by ascending waters alone are the copper deposits of Lake Superior. These deposits, while very bunchy and extremely irregular in the distribution of copper, are wonderfully persistent in depth. The copper of the ore was deposited in the metallic form. As compared with sulphides, this material is not readily oxidized. In this district the rocks above the level of groundwater are not appreciably weathered. Doubtless there was a belt of weathered material before the glacial epochs, but if so, it has been swept away by ice erosion; and since the glacial period sufficient time has not elapsed to weather appreciably the rocks which now lie within the theoretical belt of weathering. If there once were in this district an upper belt of weathering in which there were deposits of exceptional richness, this

material has been removed. However, in this district, a first concentration by ascending waters was adequate, but it is not often that a first concentration produces deposits of such richness as those adjacent to Calumet and Houghton on Keweenaw Point; and, indeed, this is exceptional even in the Keewenawan of the Lake Superior region; for while concentrations of copper have occurred at many points in the rocks of this period, as yet at no other locality have those concentrations been found to be so abundant and rich as to warrant exploitation on a large scale.

I now turn to the question as to the cause of frequent diminution of richness of ore deposits with depth. Many or most of such ore deposits are believed to be the products of two concentrations, the first by ascending, the second by descending waters. In this connection it is necessary to call attention to the fact that a large proportion of the ore deposits which are being exploited are below some part of a slope. It may be said that the reason for this is that the low grounds are more difficult to explore and work; but giving due allowance for this, it still seems to me that the majority, perhaps the great majority, of very rich deposits are below slopes and crests, and not below the valleys. I believe the richer deposits are below the slopes, because at these places a second concentration is possible and probable.

Returning now to this chart (Fig. 6) we shall direct our attention to the fissure on the slope. This fissure once extended up through the overlying rocks which have been removed by denudation. What has become of the ore in the part of the fissure which has been worn away? If, for instance, it carried 5 per cent. of copper, what has become of it? A part of it would have been scattered far and wide through erosive action; but a part of it would have been taken into solution and redeposited in the same vein deeper down. In the belt of weathering oxidized salts, such as sulphates, would form; the descending waters would carry these products downward; and it is my belief that they would react upon the solid, lean sulphides below with the result of precipitating the metals from the descending solutions.

Now this has been held to be a mere unverified assumption by some geologists, but it seems to me that they have not fully considered the certain effects of the chemical laws concerned. We know if in a laboratory a solution of copper sulphate or other copper salt be placed in contact with iron sulphide, that copper will be thrown down as copper sulphide. If the copper solution be placed in contact with a lean copper-iron sulphide, a sulphide richer in copper will be produced. And if these reactions occur in the chemical laboratory, will they not as certainly occur in the laboratory of nature, although perhaps more slowly?

At this point it is to be recalled that in many copper deposits above the level of groundwater oxides and carbonates occur, while below the level of groundwater are sulphides. Moreover, at high levels these sulphides are rich in copper, and they usually become poorer in copper sulphide and richer in iron sulphide at the lower levels. You will remember at Butte, Mont., at and for a distance below the level of the groundwater, are rich copper sulphurets which grade at depth into leaner copper sulphides containing correspondingly large amounts of iron sulphide. You will remember the same is true for the entire Appalachian region. You will remember that frequently above the level of groundwater gold lodes are exceedingly rich. What is the explanation of these and similar facts? What is the explanation of the exceptional or even extraordinary richness of the deposits at and near the level of groundwater, and of the low grade of cupriferous pyrites deep below the level of groundwater. In my opinion the only plausible explanation is that the rich parts of the deposits have received two concentrations, the first by ascending waters and the second by descending waters. The metals of the rich portions of the deposits were largely contributed by the parts of the deposit above, or once above, the rich parts. In some cases portions of the depleted veins remain, as at Butte; but frequently the depleted parts of the veins have been removed by erosion. The remote source of the material was, therefore, the metals deposited by the first concentration.

But let us follow the matter still farther. In the majority of cases, as denudation continued, the parts of the ore deposits produced by the second concentration rise into the belt of weathering. They may there be partly or wholly transformed into rich oxidized products, or they may be depleted to extend the rich deposits below. In the concentration by descending waters the chief chemical reactions are believed to be between the oxides or salts of copper and the sulphide of iron. The precipitation of copper sulphide resulting may occur in various ways.

The reaction may produce chalcopyrite, as shown by the following equations:

$CuSO_4 + 2FeS = CuFeS_2 + FeSO_4$, or

$CuSO_4 + 2FeS_2 + O_4 = CuFeS_2 + FeSO_4 + 2SO_2$.

The reactions may produce bornite, as shown by the following equations:

$Cu_2SO_4 + CuSO_4 + 3FeS = Cu_3FeS_3 + 2FeSO_4$, or

$Cu_2SO_4 + CuSO_4 + 3FeS_2 + 6O = Cu_3FeS_3 + 2FeSO_4 + 3SO_2$.

Or the reactions may directly produce chalcocite, as shown by the following equations:

$Cu_2SO_4 + FeS = Cu_2S + FeSO_4$, or

$Cu_2SO_4 + FeS_2 + O_2 = Cu_2S + FeSO_4 + SO_2$.

If the reactions are between a copper salt and sulphide bearing copper various reactions throwing down the copper may also occur. The reactions may be upon chalcopyrite producing bornite, as shown by the following equation:

$2CuFeS_2 + CuSO_4 + O_2 = Cu_3FeS_3 + FeSO_4 + SO_2$.

It may be the reaction of copper sulphate upon chalcopyrite or bornite producing chalcocite, as shown by the following:

$CuFeS_2 + CuSO_4 + O_2 = Cu_2S + FeSO_4 + SO_2$, or

$Cu_3FeS_3 + CuSO_4 + O_2 = 2Cu_2S + FeSO_4 + SO_2$.

It may be by the reaction of copper oxide or copper sulphate upon covellite producing chalcocite, as shown by the following equations:

$6CuS + 2Cu_2O = 5Cu_2S + SO_2$, and

$6CuS + 2Cu_2SO_4 + 3H_2O = 5Cu_2S + 2H_2SO_4 + H_2SO_3$.

Parallel sets of reactions could be, and indeed are written in my full paper upon the subject of ore deposits, which explain the formation of the rich sulphides of lead, zinc, and silver through the reactions of the oxidized products of these metals upon sulphide of iron, producing rich sulphides of lead, zinc, and silver. However time does not suffice to present these this evening. The particular reaction in an individual case will depend upon the relative solubilities of the various compounds present, upon the law of mass action, upon the pressure and temperature, and upon various other factors.

Now I do not assert of the equations which have been written for copper and the other metals that the reactions represented occur exactly as written, but I do assert that reactions of the general character represented occur by which the oxidized products of the metals in solution are thrown down by the lean sulphurets, producing rich sulphurets. I have no doubt that many other reactions besides those written take place. It is exceedingly difficult to ascertain the particular reactions which occur at a given time and place; but I think it is perfectly clear that reactions occur of the type of those written. I cannot attempt to give you all the evidence on the point, but to me the case is demonstrative. If this be correct we now have an explanation of the fact that a great many ore deposits are rich at high levels and become poorer with depth. These ore deposits have undergone two concentrations, a first concentration deposited by ascending waters and a second concentration deposited by descending waters. The supplies for the first concentration were obtained from the widely dispersed and small amounts of material disseminated through the rocks. The supplies for the second concentration were derived from an earlier concentration.

In the foregoing statements the second concentration of metals by solution, downward transportation, and precipitation by reactions upon the sulphides of an earlier concentration has been emphasized. However, it is not supposed that this is the only process which may result in enrichment of the upper parts of ore-deposits by descending waters. The enrichment of this

belt may be partly caused (1) by reactions between the downward moving waters carrying metallic compounds and the rocks with which they come in contact, and (2) by reactions due to the meeting and mingling of the waters from above and the waters from below.

(1) The metallic compounds dissolved in the upper part of the veins, carried by descending waters, may be precipitated by material contained in the rocks below. This material may be organic matter, ferrous substances, etc. So far as precipitating materials are reducing agents, they are likely to change the sulphates to sulphides, and precipitate the metals in that form. While sulphides may thus be precipitated either above or below the level of groundwater, they are more likely to be thrown down below the level of groundwater. Other compounds than reducing agents or sulphides may precipitate the downward moving salts in other forms than sulphides.

(2) In a trunk-channel, where waters ascending from below meet waters descending from above, there will probably be a considerable belt in which the circulation is slow and irregular, the main current now moving slowly upward and now moving slowly downward, and at all times being disturbed by conventional movements. Doubtless this belt of slow general movement and conventional circulation would reach a lower level at times and places of abundant rainfall than at other times and places, for under such circumstances the descending currents would be strong. The ascending currents, being controlled by the meteoric waters falling over wider areas, and subject to longer journeys than the descending currents, would not so quickly feel the effect of abundant rainfall. Later, the ascending currents might feel the effect of the abundant rainfall and carry the belt of upward movement to a higher level than normal. However, where the circulation is a very deep one, little variations in ascending currents result from irregularities of rainfall.

In the belt of meeting ascending and descending waters (see Fig. 6) conventional mixing of the solutions due to difference in temperature would be an important phenomenon. The waters

rom above are cool and dense, while those from below are warm and less dense. In the neutral zone of circulation the waters from above would thus tend to sink downward, while waters from below would tend to rise, and thus the waters would be mingled. Still further, even if the water were supposed to be stagnant at the neutral belt, it is probable that by diffusion the materials contributed by the descending waters would be mingled with the materials contribùted by the ascending waters.

Ascending and descending solutions are sure to have widely different compositions, and precipitation of metalliferous ores is a certain result. As a specific case in which precipitation is likely to occur, we may recall that waters ascending from below contain practically no free oxygen and are often somewhat alkaline, while waters descending from above are usually rich in oxygen and frequently contain acids, as at Sulphur Bank, described by Le Conte.[1] The mingling of such waters as these is almost sure to result in precipitation of some kind. Le Conte further suggests[2] by the mingling of the waters from below with those from above that the temperature of the ascending column will be rapidly lessened, and this also may result in precipitation, but the dilution would work in the reverse direction.

The metals precipitated by the mingling of the waters may be contributed by the descending waters, by the ascending waters, or partly by each. In so far as more than an average amount of metallic material is precipitated from the ascending waters, this would result in the relatively greater richness of the upper part of veins independently of the material carried down from above.

In all the cases considered the precipitation and enrichment of the upper parts of deposits follow from the reactions of downward moving waters. Their effect may be to precipitate the metals of the ascending water to some extent and thus assist in the first concentration. But the results of these processes

[1] On the Genesis of Metalliferous Veins, by JOSEPH LE CONTE: Am. Jour. Sci., 3d ser., Vol XXVI, 1883, p. 9.

[2] LE CONTE, op. cit., p. 12.

cannot be discriminated from the concentration resulting from an actual downward transportation of the material of an earlier concentration. In concluding this part of the subject, *It is held that the downward transportation of metals already in lodes is the most important of the causes explaining the character of the upper portions of ore deposits; and that their peculiar characters are certainly due to the effect of descending waters.*

The concentrations by ascending and descending waters have been considered as if they were mainly successive. In some instances this may be the case; but it is much more probable that ascending and descending waters are ordinarily at work upon the same fissure at the same time, and that their products are, to a certain extent, simultaneously deposited. For instance, under the conditions represented by this chart (Fig. 6) a first concentration by ascending waters is taking place in the lower part of the fissure, and a reconcentration by descending waters is taking place in the upper part of the fissure. Between the two there is a belt in which both ascending and descending waters are at work. The rich upper part of an ore deposit which is worked in an individual case may now be in the place where ascending waters alone were first acting, where later, as a consequence of denudation, both ascending and descending waters were at work, and still later, where descending waters alone are at work. The more accurate statement concerning ore deposits produced by ascending and descending waters, is, therefore, that ascending waters are likely to be the potent factor in an early stage of the process, that both may work together at an intermediate stage, and that descending waters are likely to be the potent factor in the closing stage of the process.

Also, for the sake of simplicity in the consideration of the concentrations I have disregarded the lateral elements of the moving water. In many cases superimposed upon the vertical movements in the fissures or other openings are lateral movements, as a result of which the deposits instead of being in vertical positions are inclined, often much inclined, and indeed may be horizontal or even locally descending. Moreover the

horizontal extents of the deposits may be much greater than the vertical extents. Reduced to a simple and broad statement, *The first concentration of many ore deposits is the work of a relatively deep water circulation, while the reconcentration is the result of reactions upon an earlier concentration through the agency of a relatively shallow water circulation. Commonly the deep water circulation is lacking in free oxygen and contains reducing agents, and the shallow water contains free oxygen. The deep water is therefore a reducing, and the shallow water an oxidizing agent.*

In addition to the general factors already considered there are many special factors which have a most important, indeed, very often a controlling influence in the production of ore-chutes and in the localization of ore in certain areas and districts. Some of these factors are the complexity of openings, the presence of impervious strata at various depths, the presence of pitching folds, the character of the topography. I see however that my time is nearly gone, and I shall not take up their discussion this evening, but must refer those especially interested in this phase of the subject to my full paper already repeatedly mentioned.[1] I must however note that impervious strata are frequently of controlling importance in the underground circulation. Often deep and shallow water circulations are separated by such strata. Often also as the result of the removal of impervious strata by denudation, the previous deep circulation ceases and the action of the shallow circulation is inaugurated.

At this point it may be well to briefly recall the most fundamental features of the water circulation which produces the ore deposits. First comes the downward-moving, lateral-moving waters of meteoric origin which take into solution metalliferous material. These waters at depth are converged into trunk channels, and there, while ascending, the first concentration of ore deposits may result. After this first concentration many of the ore deposits which are worked by man have undergone a later concentration not less important than the earlier, as a result of

[1] Some Principles Controlling the Deposition of Ores, by C. R. VAN HISE : Trans. Am. Inst. Min. Eng., Vol. XXX, 1900, pp. 112–146.

shallow descending or lateral-moving waters. In other cases a concentration by descending, lateral-moving waters alone is sufficient to explain some ore deposits. It thus appears more clearly than heretofore that an adequate view of ore deposits must not be a descending-water theory, a lateral-secreting water theory, or an ascending-water theory alone. While an individual ore deposit may be produced by one of these processes, *For many ore deposits a satisfactory theory must be a descending, lateral-secreting, ascending, descending, lateral-secreting theory.*

But there is no question in my mind that this theory is still insufficient to fully explain many of the ore deposits. No knowledge is ever complete. We move step by step, carrying a theory nearer and nearer completion. If, however, a theory be based on good work, it usually will not prove to be false; it will be found to be incomplete. Sandberger was not wrong when he said lateral secretion explained many things in reference to ore deposits. He was wrong only when he excluded other factors. He became unscientific when he carried his theory further than his observations justified. While the theory here proposed is believed to make an important advance, it will sooner or later be found to be incomplete. I trust it will not be found to be false. But the most that I can hope for it is that it is approximately correct as far as it goes.

It is believed that the principles which have been presented lead to a new and natural classification of the ore deposits produced by underground water. As already noted, ore deposits may be divided into three groups: (1) ores of igneous origin, (2) ores which are the direct result of the processes of sedimentation, and (3) ores which are deposited by underground water.

Since the ores produced by igneous agencies and those produced by processes of sedimentation have not been considered in this paper, a subdivision of these groups will not be attempted.

Ores resulting from the work of groundwater, group (3) above, may be divided into three main classes:

(*a*) Ores which at the point of precipitation are deposited by ascending waters alone. These ores are usually metallic or

some form of sulphuret; but they may be tellurides, silicates, or carbonates.

(*b*) Ores which at the place of precipitation are deposited by descending waters alone. These ores are ordinarily oxides, carbonates, chlorides, etc., but silicates and metals are exceptionally included.

(*c*) Ores which receive a first concentration by ascending waters and a reconcentration by descending waters. The concentration by ascending waters may wholly precede the concentration by descending waters, but often the two processes are at least partly contemporaneous. The materials of class (*c*) comprise oxides, carbonates, chlorides, and rarely metals and silicates above the level of groundwater, and rich and poor sulphurets, tellurides, metallic ores, etc., below the level of groundwater. At or near the level of groundwater, these two kinds of products are more or less intermingled, and there is frequently a transition belt of considerable breadth.

How extensive are the deposits of class (*a*) I shall not attempt to state. Indeed, I have not such familiarity with ore deposits as to entitle me to an opinion upon this point. However a considerable number of important ore deposits belong to this class. This class is illustrated by the Lake Superior copper deposits.

The ore deposits of class (*b*) are important. Of the various ores here belonging probably the iron ores are of the most consequence. A conspicuous example of deposits of this kind are the iron ores of the Lake Superior region.

It is believed that the ore deposits of class (*c*) are by far the most numerous. I suspect that a close study of ore deposits in reference to their origin will result in the conclusion that the great majority of ores formed by underground water are not the deposits of ascending waters alone, but have by this process undergone an early concentration, and that descending waters have produced a later concentration, as a result of which there is placed in the upper 50 to 500 or possibly even 1000 meters of an ore deposit a large portion of the metalliferous material

which originally had, as result of the early concentration, a much wider vertical distribution.

To the foregoing classification objections will at once be made: It will be said that there are no sharp dividing lines between the groups and classes. To this objection there is instant agreement. Transitions are everywhere the law of nature. It is well known that there are gradations between different classes of rocks,[1] and this statement applies equally well to ore deposits. I even hold that there is gradation between ore deposits which may be explained wholly by igneous agencies and those which may be explained wholly by the work of underground water or by processes of sedimentation.

I have elsewhere held that there is complete gradation between waters containing rock in solution and rock containing water in solution.[2] If there be no sharp separation between water solutions and magma it is probable that this is also true in reference to ore deposits of direct igneous origin and those produced by underground water. There may be ore deposits in which water action and magmatic differentiation have been so closely associated that one cannot say whether the resultant ore deposit is mainly a water deposit or mainly a magmatic deposit. But for the vast majority of ore deposits, if I properly apprehend the relations, the broad general statements which I have made apply. Ordinarily there is little difficulty in discriminating between veins and dikes, the first representing crystallizations from water solutions, the second crystallizations from magma. There are few cases where the discrimination in reference to ore deposits is not easy. While gradations between water deposited ores and igneous ores are uncommon, gradations between the different classes of ore deposits formed by underground water are common.

Ores which have received a first concentration by igneous agencies or by processes of sedimation are sure to be reacted upon by the circulating underground waters, and thus a second

[1] The Naming of Rocks, by C. R. VAN HISE: Journ. of Geol., Vol. VII, 1899, pp. 687, 688.

[2] Principles of North American pre-Cambrian Geology, by C. R. VAN HISE: Sixteenth Ann. Rept. U. S. Geol. Surv., 1894–5, Pt. I, p. 687.

or even a third concentration may take place. The first concentration by igneous or sedimentary processes may be the more important or dominant process, or the additional concentration or concentrations by underground waters may be the more important or dominant process. In some cases therefore the ores may be referred to as produced by igneous agencies, in others as produced by processes of sedimentation, in others as produced by these in conjunction with underground waters, and in still others as produced mainly by underground waters.

Ore deposits which are precipitated almost solely by ascending waters will grade into those in which descending waters have produced an important effect, and thus there will be transition between classes (*a*) and (*c*). Similarly there will be every gradation between classes (*a*) and (*b*) and between classes (*b*) and (*c*). If this be so it will not infrequently happen that a single fissure may fall partly in one class and partly in another. Thus a single ore deposit may belong partly in class (*a*) and partly in class (*c*). However, in most cases the workable part of a deposit will largely belong to one of the three classes.

Not only are there gradations between different varieties of the ore deposits, but there are gradations between the ore deposits and the rocks; for the ore deposits in many cases are not sharply separated from the country rocks, but grade into them in various ways.

In answer to the above objection concerning gradations, it may be said that I know of no classification of ore deposits which has yet been proposed to which the same objection may not be urged with equal or greater force.

However this retort does not give any criterion by which the usefulness of the above classification may be tested. The test is, does this classification give a more satisfactory method of studying ore deposits than has heretofore been possible? Will an attempt to apply this classification assist mining engineers and geologists in accurately describing ore deposits? Will the classification to a greater extent than any previous one give engineers rules to guide them in their expenditure in exploration

and exploitation? By these criteria I am willing that the classification shall be tested.

As an illustration of the practical usefulness of the classification is the connection between genesis and depth. The character of a deposit in most cases will determine to which class it belongs. Where the ores are deposited by ascending waters alone it has been pointed out that this is favorable to their continuity to great depth. Therefore, where a given ore deposit has been shown to belong to this class, the expenditure of money for deep exploration may be warranted, although, as already pointed out, p. 757, such deposits may decrease in richness with depth. Where a deposit is produced by descending waters alone, the probable extent in depth is much more limited. In such cases, when the bottom of the rich product is reached, it would be the height of folly to expend money in deep exploration. Where the ore deposit belongs to the third class, that produced by ascending and descending waters combined, there will, again, be a richer upper belt composed of rich oxidized and sulphureted deposits which we cannot hope will be duplicated at depth. To illustrate: it would be very foolish, at Ducktown, Tenn., to sink a drill hole or shaft into the lean cupriferous pyrrhotite with the hope of finding rich sulphurets such as those which were mined near the level of groundwater. Those who have spent money in deep prospecting of the lean pyrrhotite in the Appalachian range will doubtless agree to this statement. Deposits produced by two concentrations may grade into the class produced by ascending water alone, and after the transition the deposit may be rich enough to warrant exploitation at depth; but if such work be undertaken it must be done with the understanding that the rich upper products will not be reduplicated at depth. It therefore appears to me that the determination to which of the classes of ore deposits produced by underground waters a given ore deposit belongs has a direct and very important practical bearing upon its exploration and exploitation.

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